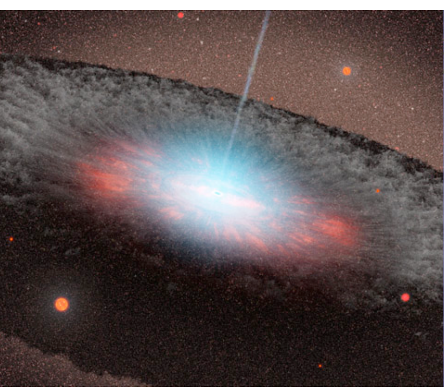
Gamma-Ray Astrophysics in the Time Domain

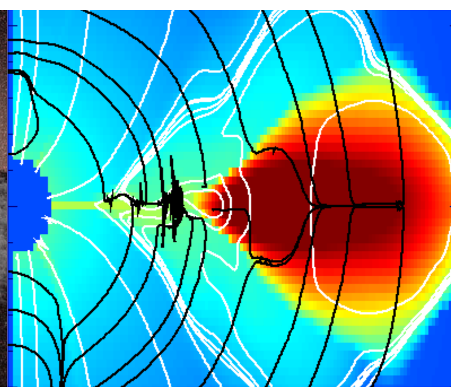
- Some Key Issues and Concepts in the Extragalactic Context -

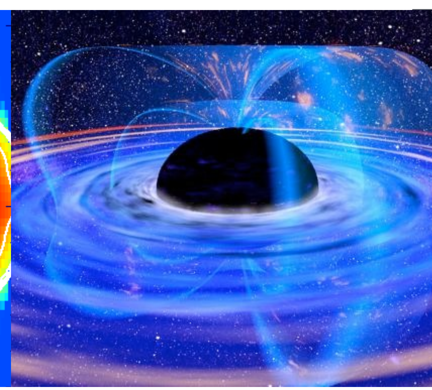
Frank M. Rieger

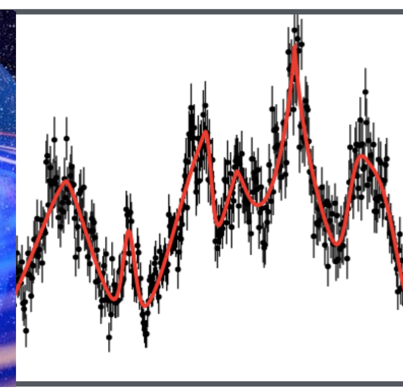
September 19, 2018

"Monitoring the Non-thermal Universe", Cochem









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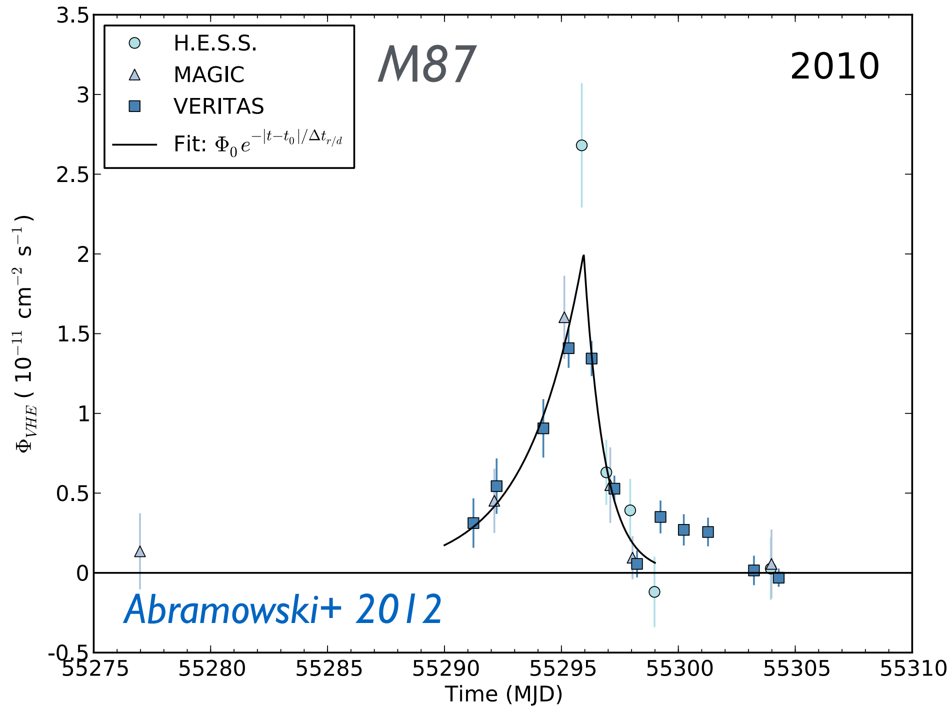
Outline

- ***Rapid VHE variability in AGN***
- ***Beyond minimum variability considerations***
  - *log-normality (PDF) and multiplicative processes*
  - *power-law noise characteristics (PSD)*
  - *year-type quasi-periodicities in blazar light curves*
- ***Potential & Perspectives***

Gamma-Ray Astronomy entering the time domain

1. Rapid VHE flux variability (minimum timescale)

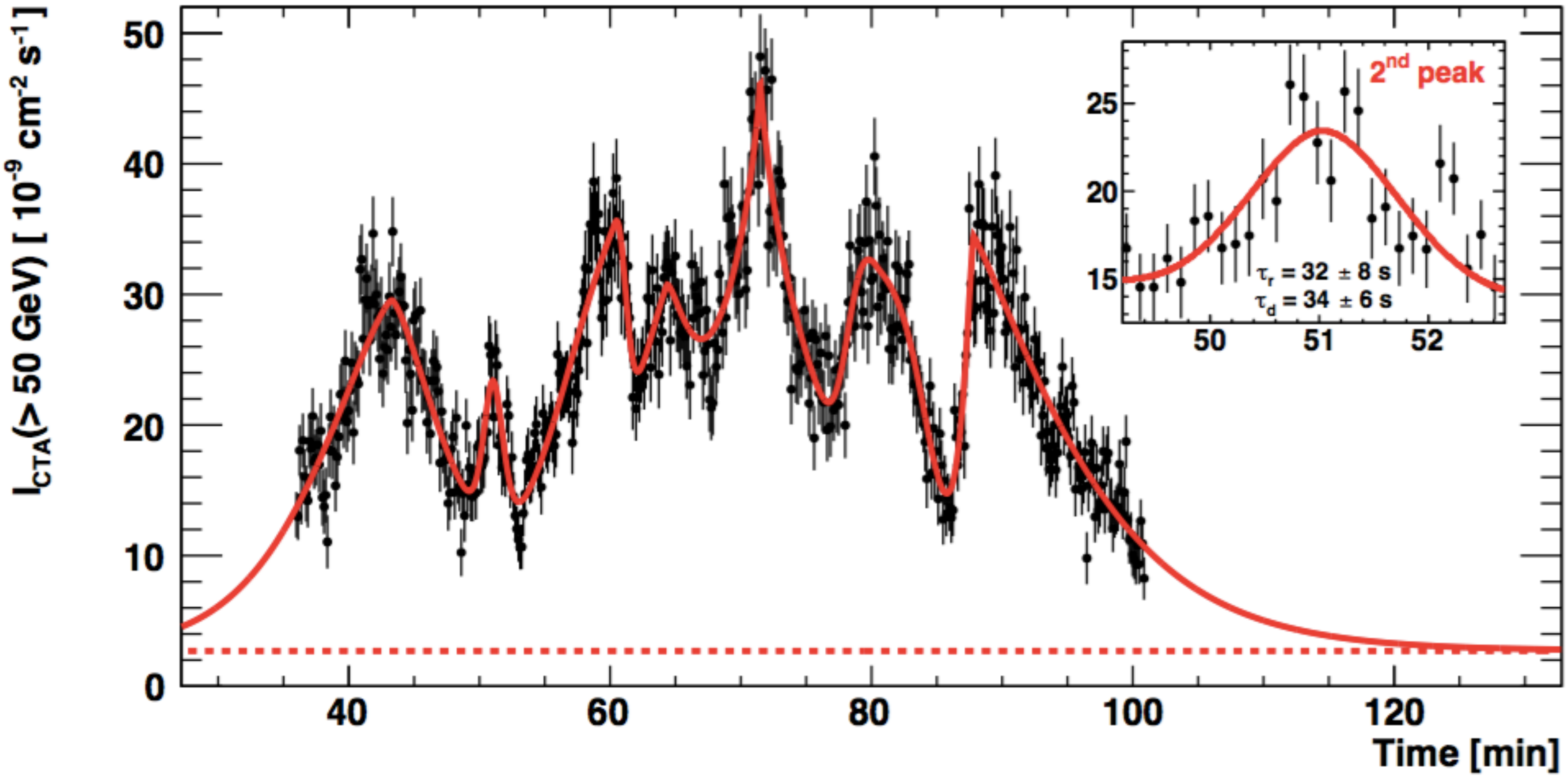
- down to minutes in bazars, e.g., **Mkn 501** (5 min), **PKS 2155-304** (3 min)
- intra-day or less in radio galaxies, e.g. **M87** (day), **IC 310** (5 min)…



‣ *extreme jet conditions:* very compact (r < δ c Δt) & luminous emitting region, close to BH? multiple (interacting) zones?

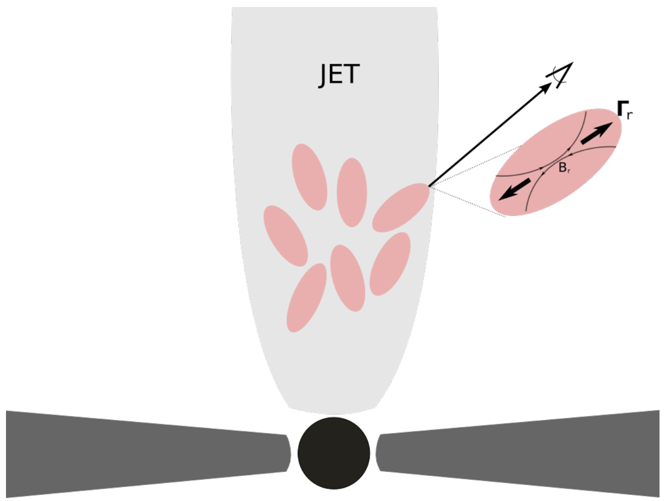
Potential will increase with CTA:

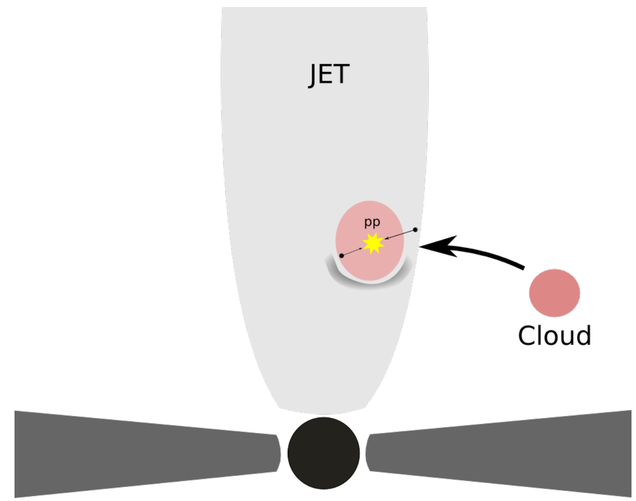
Simulated CTA light curve based on extrapolation of the power spectrum for the strong 2006 flare of PKS 2155-304 - *probing sub-min timescales*



CTA Consortium 2017

Conceptual developments include





Jets-in-Jet / Minijets:

* highly magnetized e-p - jet ($\sigma \sim 100$)
* relativistic (Petschek-type) reconnection
* additional relativistic velocity ($\Gamma_r \approx \sqrt{\sigma}$) wrt mean flow
* *differential (strong) Doppler boosting possible*
* leptonic VHE: SSC & EC by accelerated electrons

Potential challenges ?

* lower magnetization for e-p AGN jets ($\sigma \sim 10$)?
* non-negligible guide field/weak dissipation only?
* power-law e-acceleration beyond 10^2-10^3 thermal Lorentz factor $\sqrt{\sigma}\, m_p/2m_e$?

Giannios+ 2009, 2010…

Jet-star/cloud interactions:

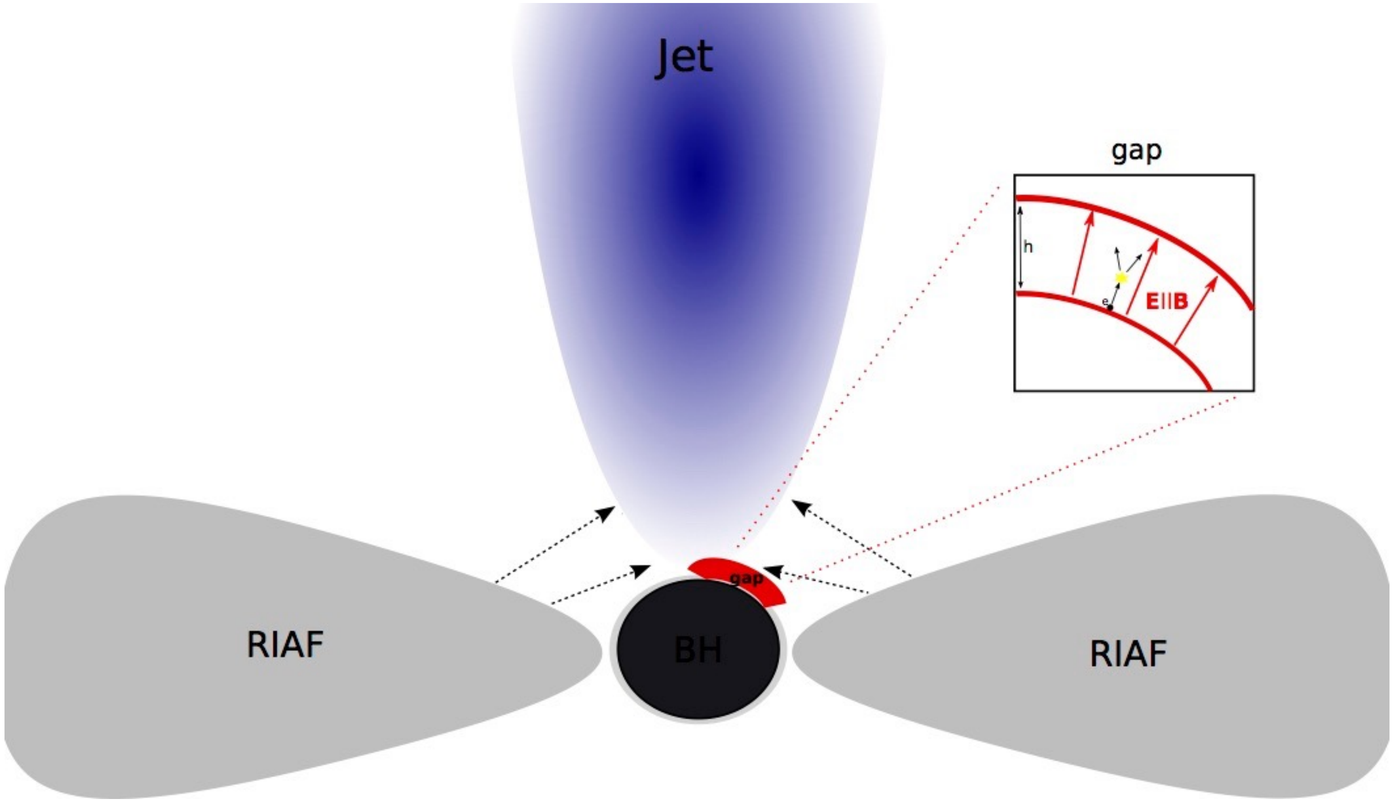
* "small" obstacle entering jet
* assume efficient (shock-type) acceleration
* hadronic VHE: pp-interactions
* high target density introduced by star/cloud
* explains light curve & spectrum

Potential challenges ?

* wide observed radio jet opening angle, very large jet power required $L_j \propto L_{VHE} \times (r_j / r_c)^2$?
* "bi-annual" frequency of interaction ?

Barkov+ 2010, 2012…

Conceptual developments include



Magnetospheric Models :

* gap-type (E_{II}) electron acceleration
* IC up-scattering of ambient disk photons
* pair cascade triggered by $\gamma\gamma$ absorption
* gap closure and MHD jet formation

Potential challenges ?

* transparency & escape of VHE (RIAF) ?
* rapid variability & possible luminosity output
  $L_{gap} \sim L_{jet} (h/r_g)^{2\text{-}4}$, $h \sim c\, \Delta t$

Levinson & Rieger 2011, Hirotani & Pu 2016, Katsoulakos & Rieger 2018…

Characterizing VHE variability in AGN

1. **Rapid VHE flux variability down to few minutes (and less/CTA)**
   - e.g., Mkn 501 (5 min), PKS 2155-304 (3 min)
   - *extreme jet conditions*, very compact & luminous region, multiple zones?

Characterizing VHE variability in AGN

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Beyond minimum variability considerations:

Characterizing VHE variability in AGN

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- e.g., Mkn 501 (5 min), PKS 2155-304 (3 min)
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Beyond minimum variability considerations:

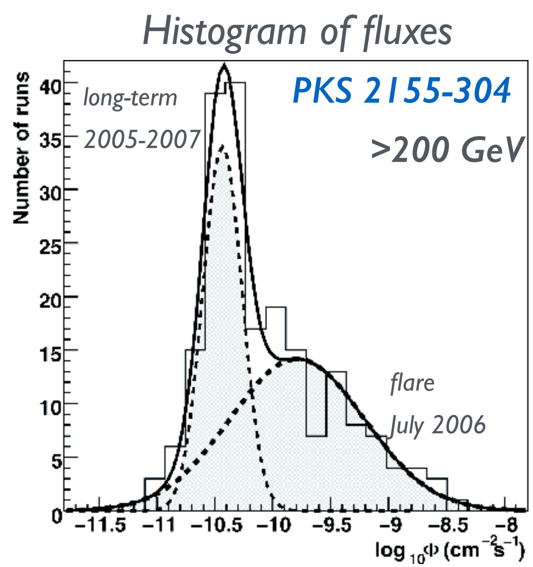
II. Evidence for log-normal distribution of fluxes

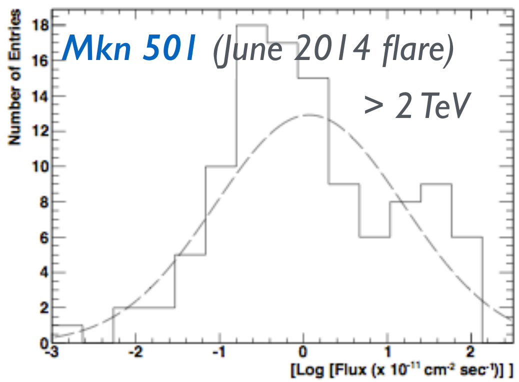
- ***Log(Flux) is Gaussian distributed***
  - for both low & high VHE source states

- *multiplicative* or cascade-type process

$$X = \log F_1 + \log F_2 + \ldots = \log(F_1 * F_2 \ldots)$$

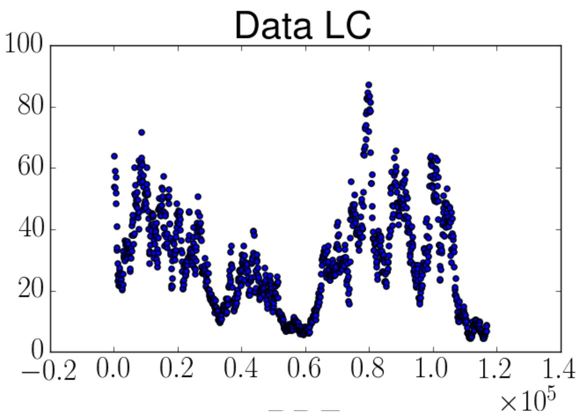
  - additive models no longer likely (*shot-noise; mini-jets…*)
  - hadronic cascade emission ? (*but different energy bands*)
  - cascade injection…





H.E.S.S. Collab., 2010 & 2015

III. Power Spectral Density (PSD)



- which power at which (temporal) frequency?
  How is variability on different timescales related to each other?
- ~modulus-squared of discrete FT (frequency domain)
  - ***"AGN vary more strongly towards longer timescales"***
  - power-law noise $P(\nu) \sim \nu^{-\alpha}$

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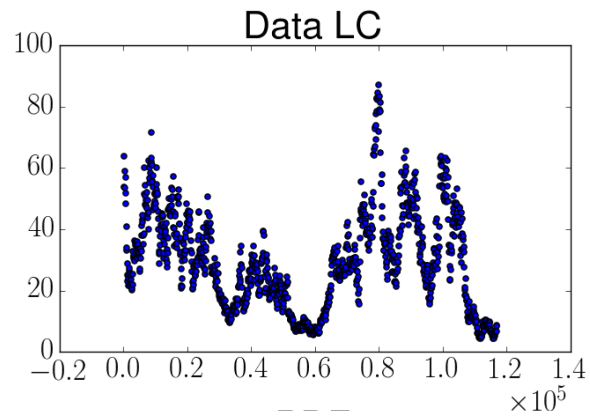
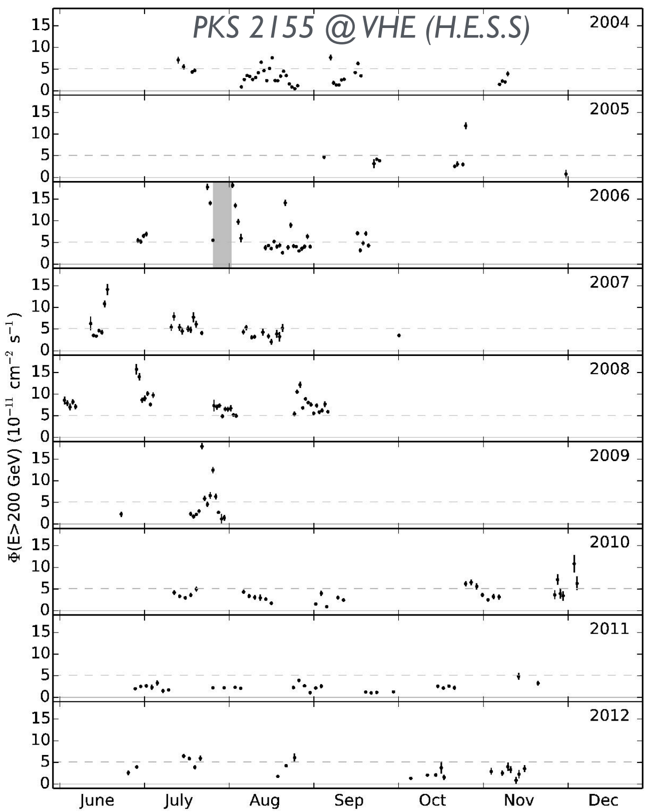


- Example: PKS 2155-304:
  - α ~ 2 for VHE active/flare states
  - α ~ 1 for quiescent HE & VHE

flare: timescales < 3h

quiescent: timescales > 1d (H.E.S.S.) > 10 d (Fermi)

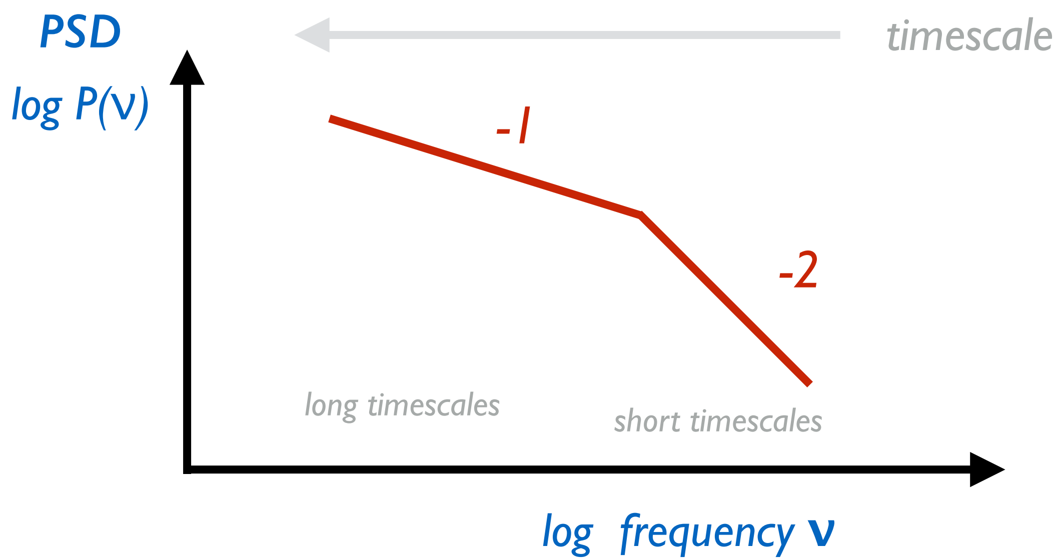


H.E.S.S. Collab., 2010, 2017

Characterizing VHE variability in AGN

- PSD break by $\Delta\alpha=1$ (around ~1 day) as in Seyfert AGN (X-ray) ?

Uttley & McHardy 2005…



- change in accretion flow conditions ? *Lyubarskii 1997…*

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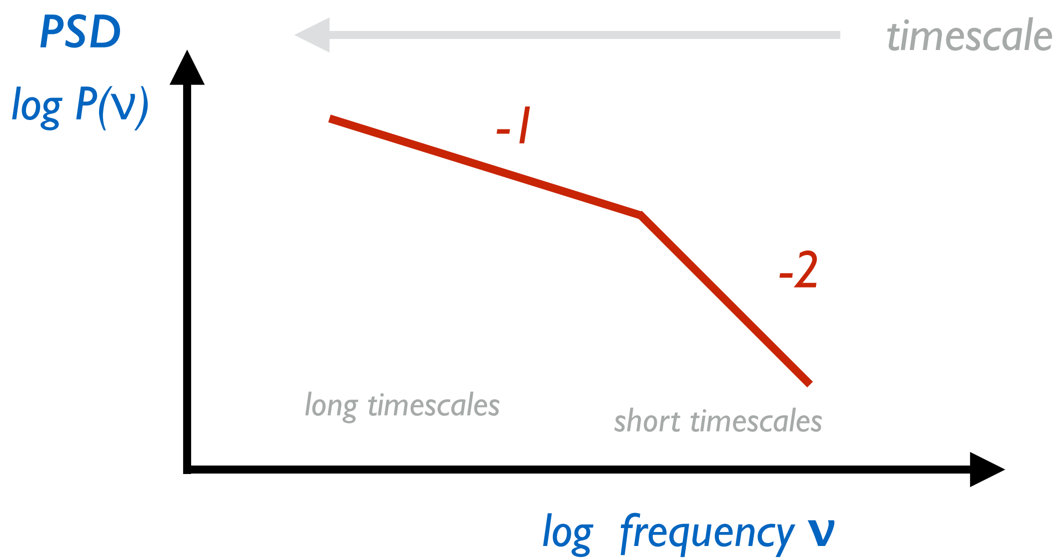
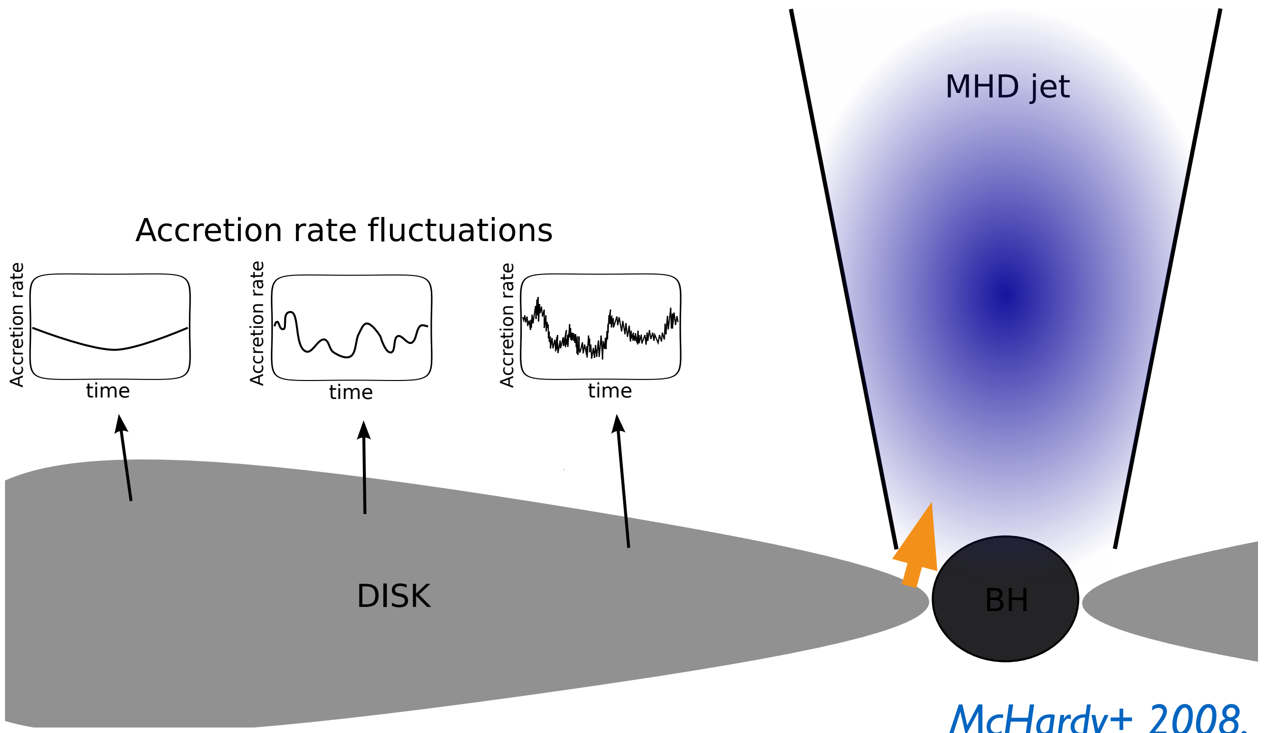


- change in accretion flow conditions ? *Lyubarskii 1997…*

Note: need to be consistent (TK'95 vs Emmanoulopoulos+ '13 simulations)

Ansatz A: disk-origin of jet

- *accretion disk variations as multiplicative, power-law noise (X-ray binary context!)*
  - *independent fluctuations on local viscous timescales $t_v(r) \sim (1/\alpha)\ (r/h)^2 (r/r_g)^{3/2}\ r_g/c$* *(Lyubarskii 1997)*
- *if efficiently transmitted to jet, power-law noise in injection for Fermi acceleration*



McHardy+ 2008, Rieger & Volpe 2010

I. Concepts: On the origin of log-normality

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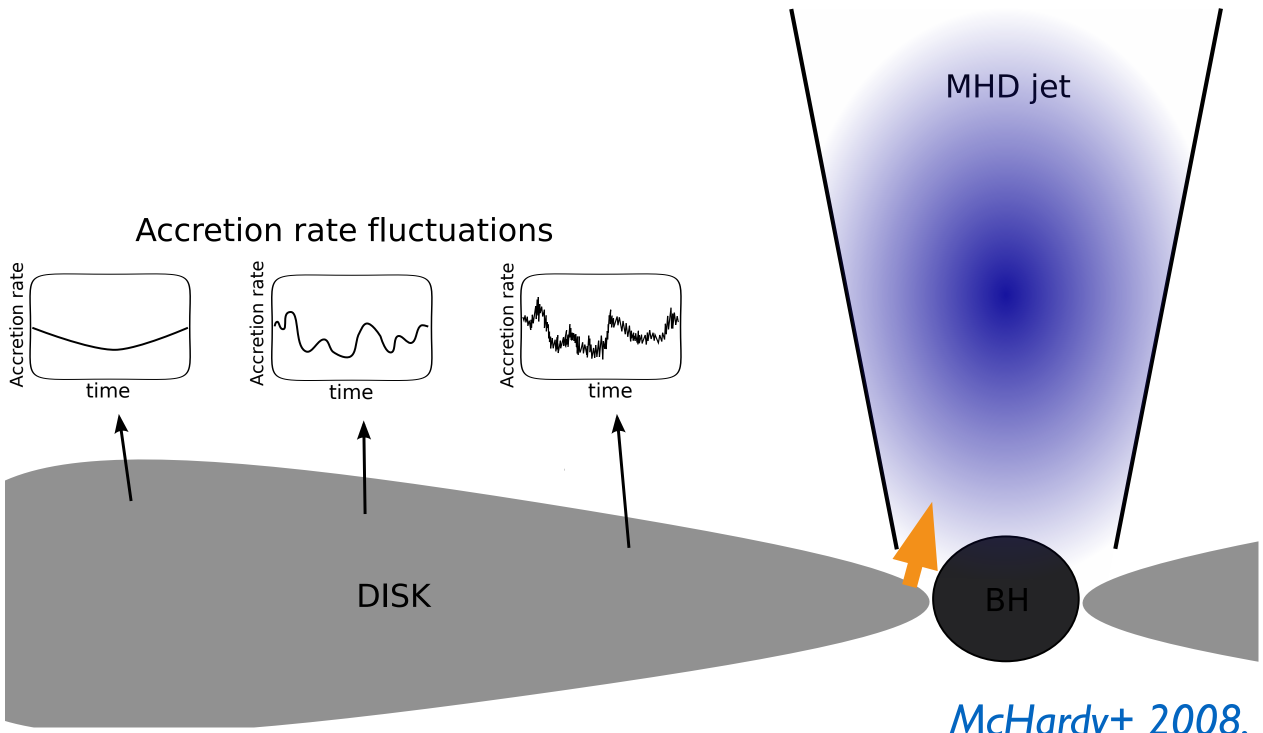


Multi-wavelength probes important

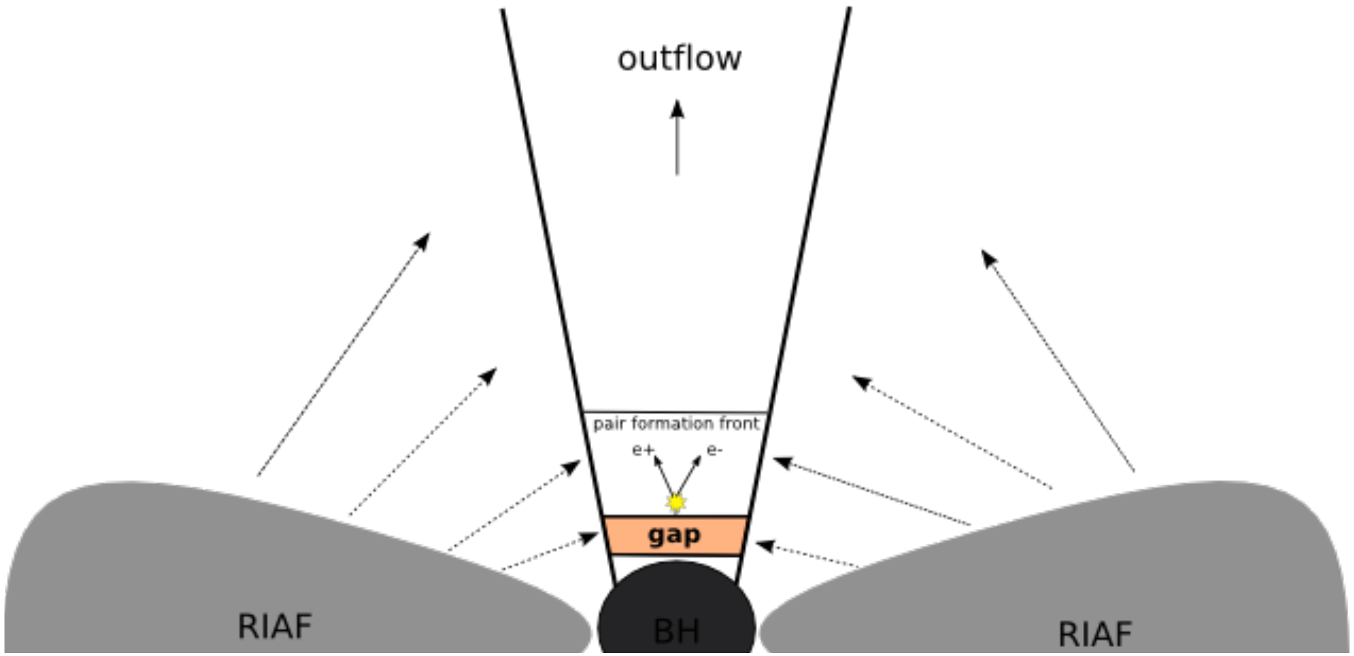
McHardy+ 2008, Rieger & Volpe 2010

I. Concepts: On the origin of log-normality

Ansatz B: plasma-generation via pair cascades

- *BH jet - vacuum gap ?*
  - *but: timescale-range typically limited (gap closure) - flares ? Unsteady gaps ?*
- *proton-induced (e.g., synchrotron-supported) cascades ("secondary" pairs)?*
  - *but: timescale-range limited (source size) - flares ?*

    & also seen at different energies (optical, X-ray, VHE) ?



Levinson & Rieger 2011

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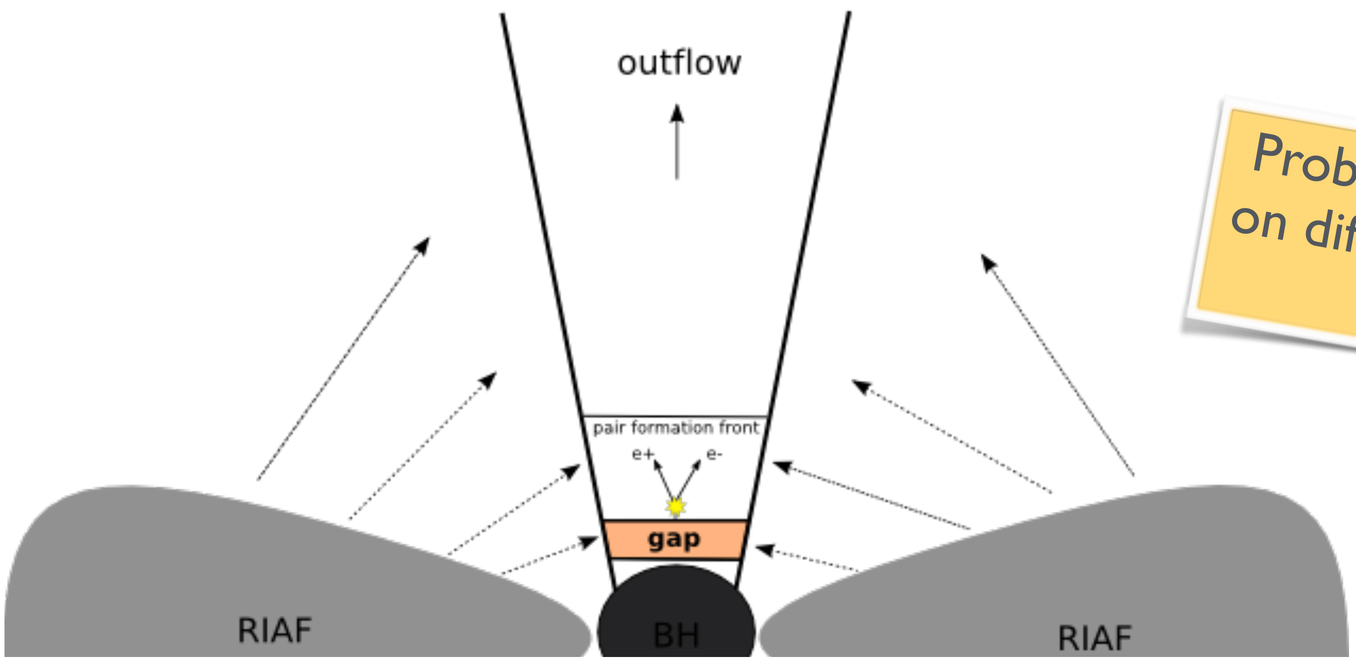
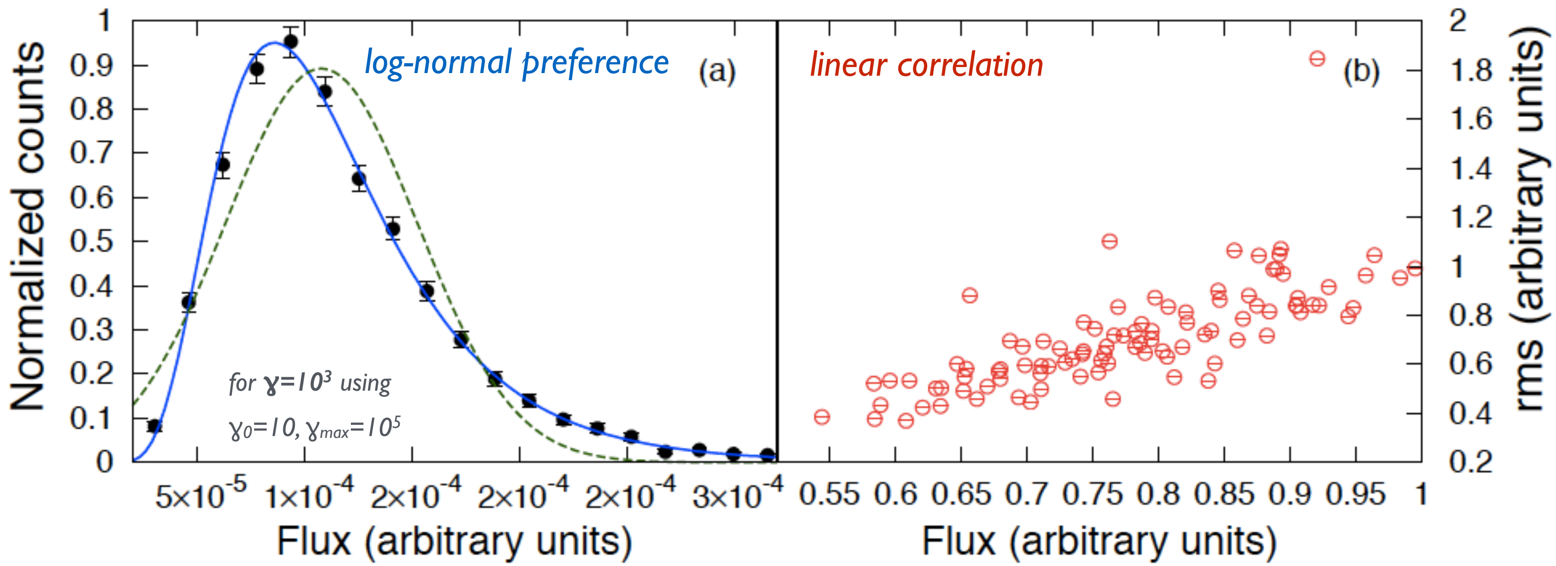


Probing log-normality on different timescales important

Levinson & Rieger 2011

Ansatz C: random fluctuations in particle acceleration rate (Sinha+ 2018)

- *random perturbations in acceleration time scale*
  - *Accelerated particle distribution:* $n(\gamma) = \gamma^{-1-t_{acc}/t_{esc}} (1-\gamma/\gamma_{max})^{t_{acc}/t_{esc}-1}$ ... *(Kirk, FR & Mastichiadis 1998)*
  - *if diffusion has Gaussian perturbations:* $t_{acc} \sim \kappa/u_s^2 \Rightarrow t_{acc} = t_{acc,0} + \Delta t_{acc}$
  - *fractional variability* $\Delta n(\gamma) / n(\gamma)$ *contains log(γ)-terms*
  - *can have log-normal shape for synchrotron and external IC…*



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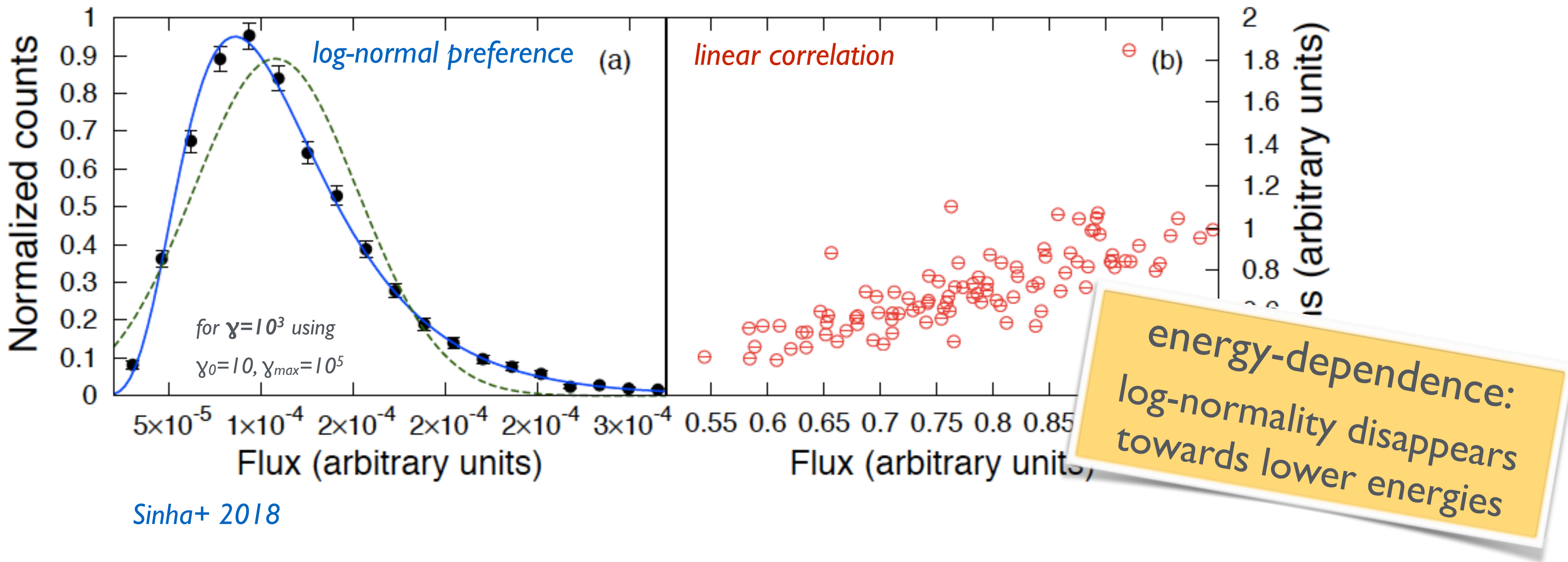

Sinha+ 2018

II. Concept: PSD-slope dependencies

Explore possible modifications of PSD-shape by radiation *(Finke & Becker 2014, 2015)*

- *start from some time-dependent particle transport equation for $N_e(\gamma, t)$*
- *Fourier transform equation ⇒ $\tilde{N}_e(\gamma, f)$*
- *inject power-law noise $\mathbb{Q}(\gamma, f) \sim f^{-\beta}$*
- *study impact on synchrotron, EC and SSC*
  - *PSD proportional $|\mathcal{F}_{SSC}(f)|^2 \sim f^{-(4\beta-2)}$ versus $|\mathcal{F}_{EC}(f)|^2 \sim f^{-2\beta}$ ($\mathcal{F}$ Fourier transform of flux)*
  - *differences for FSQP (EC) and BL Lacs (SSC) ?*

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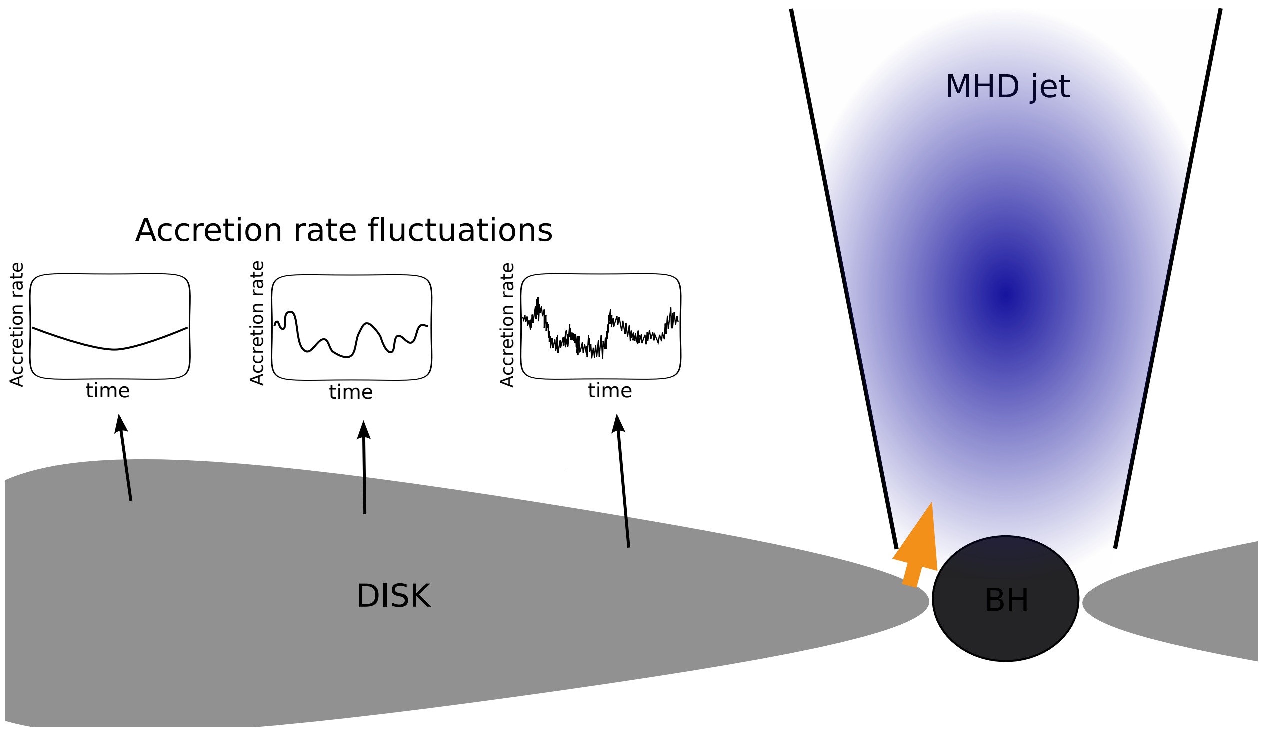
EC and SSC show different dependencies, i.e. ***2β*** *versus* ***$(4\beta-2)$***

e.g. for ***PKS 2155-304*** *(SSC):* ***$\beta \sim 1$ (flare), $\beta \sim 0.75$ (quiescent)***

Interlude: On the VHE characteristics of PKS 2155-304

Is the VHE variability driven by accretion disk fluctuations ?

- *accretion disk variations as multiplicative, power-law noise* *(Lyubarskii 1997)*
- *if efficiently transmitted to jet, power-law noise in injection for Fermi acceleration*
  - *need to study the scales on which this gets blurred by radiation etc* *(Rieger & Volpe 2010)*
  - *in particular, minimum VHE variability (~3min) limits BH size*



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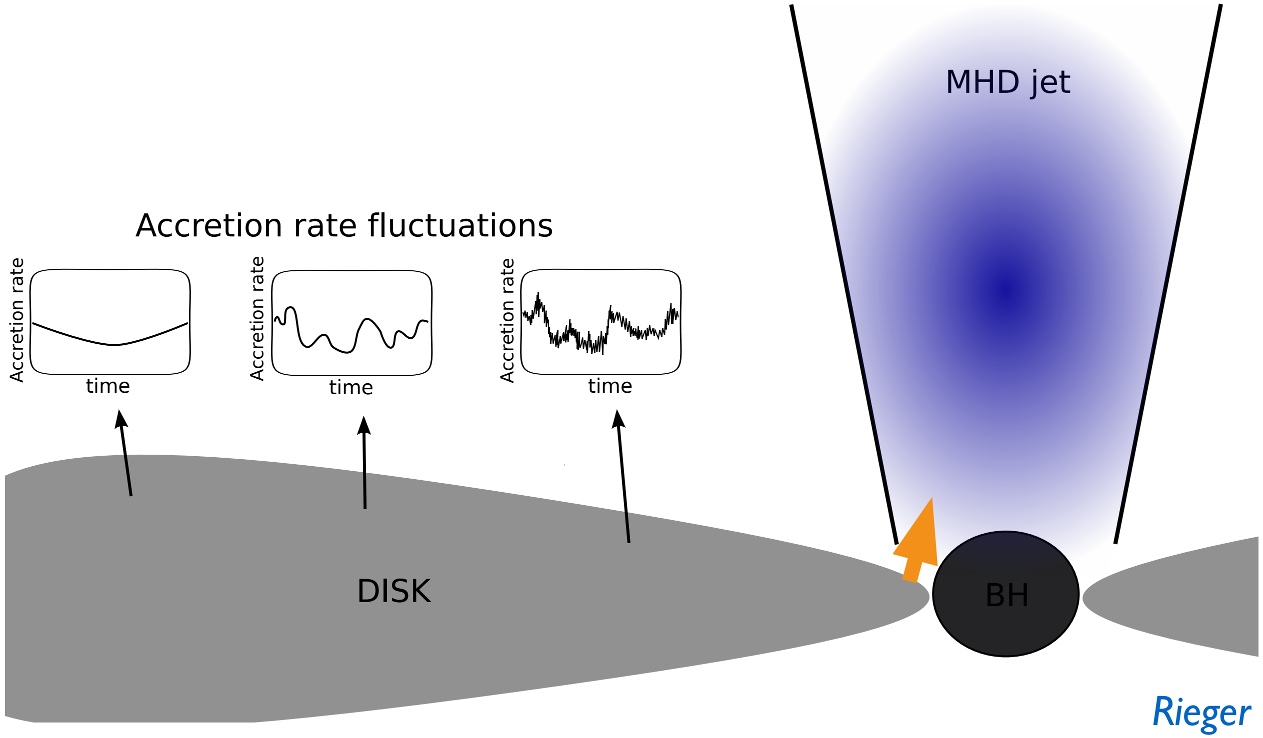

possible disk-origin of jet

Rieger & Volpe 2010; Volpe & Rieger 2011

Interlude: On the VHE characteristics of PKS 2155-304

The "cost" for it in the case of PKS 2155-304:

- *only works for "small" black hole* $\sim 3 \times 10^7 M_{sun} < M_{BH\ total}$ (from $M_{BH\ total} - L_{bulge}$)

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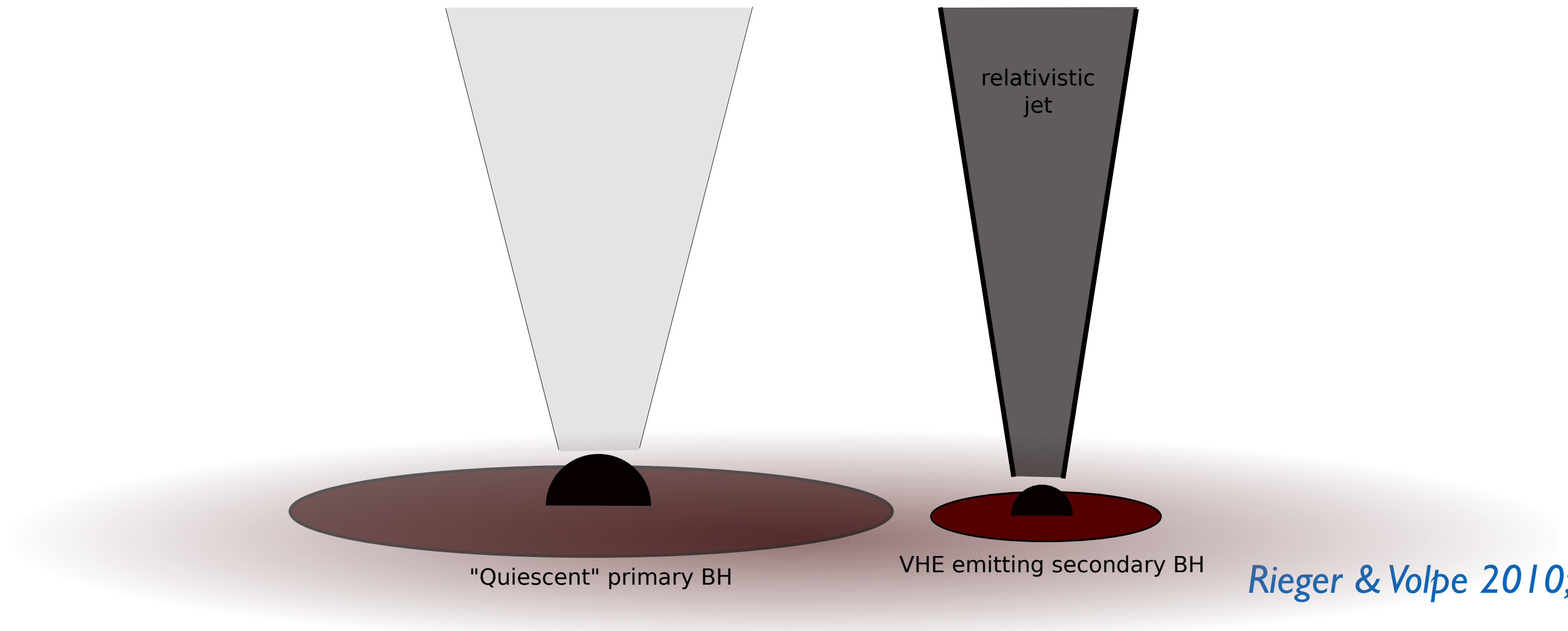
The "cost" for it in the case of PKS 2155-304:

- *only works for "small" black hole* ~3 x 10^7 M_{sun} < $M_{BH\ total}$ (from $M_{BH\ total}$ - L_{bulge})

- ***possible in a binary black hole system***
  - *elliptical galaxies as spiral merger results…*
  - *circumbinary disk-accretion preferentially feeds secondary BH* *(e.g., Artymowicz & Lubow 1996)*
  - *X-ray variability (PSD) support small BH mass* *(e.g., Czerny et al. 2001)*
  - *"evidence" for optical longterm periodicity (~7 yr)* *(Fan & Lin 2000)*

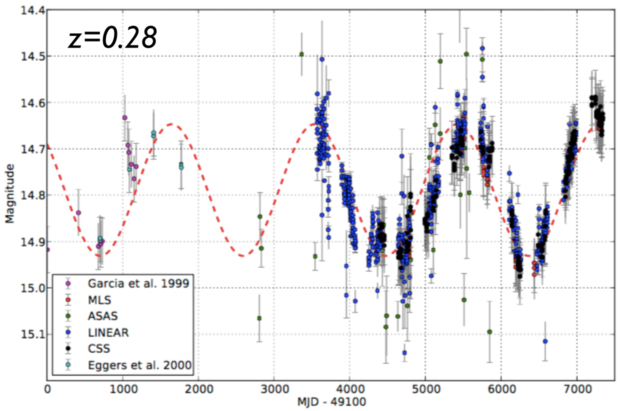


Rieger & Volpe 2010; Volpe & Rieger 2011

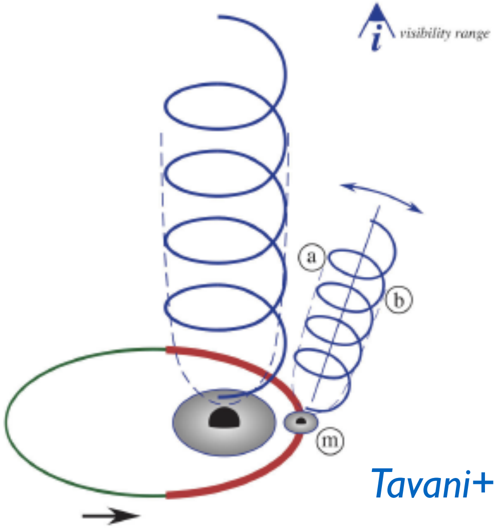
The (new) emergence of supermassive binary models

Explaining QPOs in blazar light curves:

PG 1302-102 *(optical: P = 5.2 yr)*

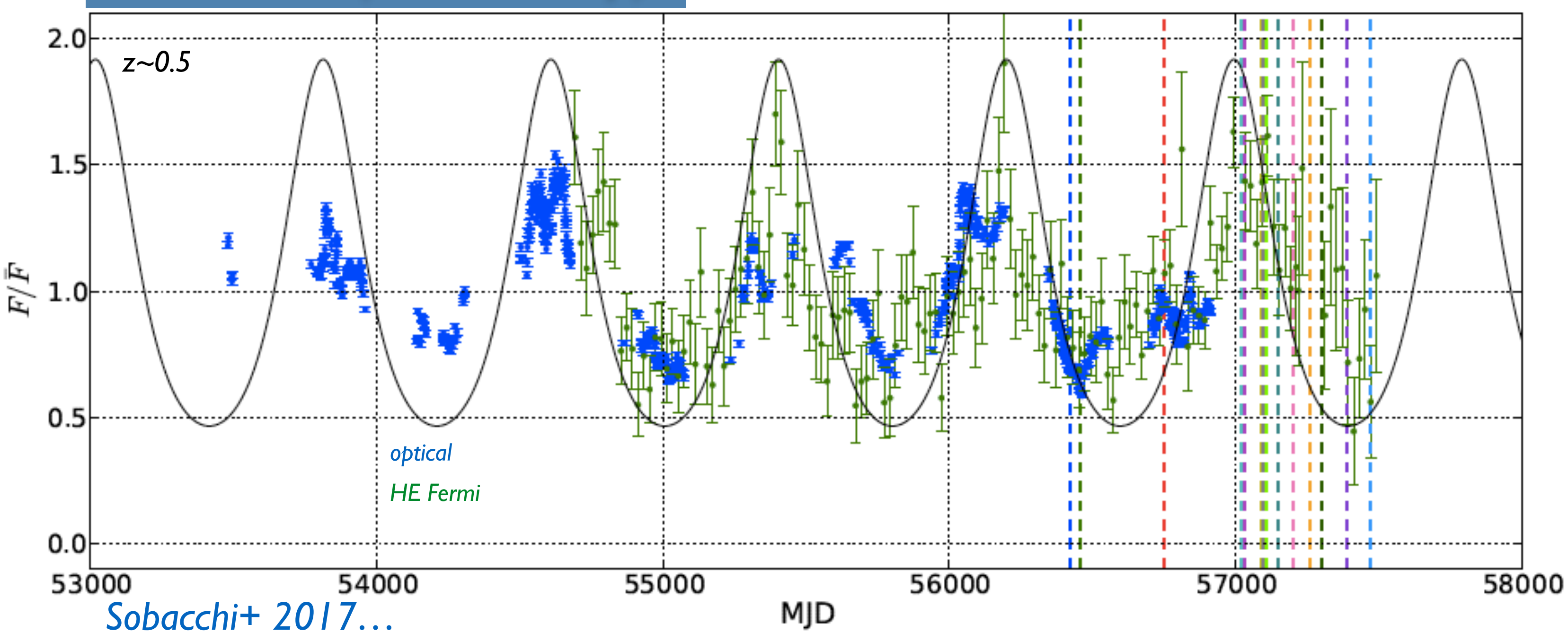


Graham+ 2015 (Nature)



Tavani+ 2018

PG 1553+113 *(Fermi: P = 2.2 yr)*



Sobacchi+ 2017…

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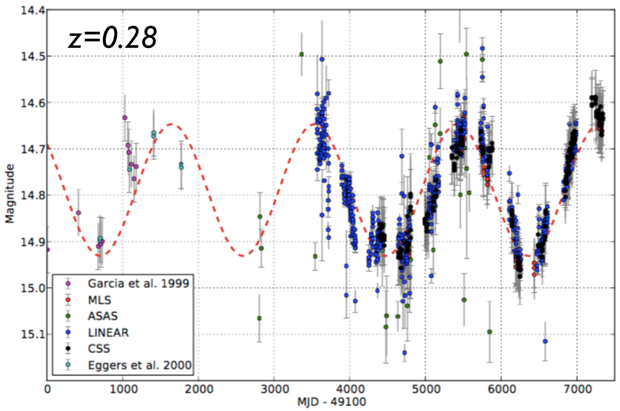

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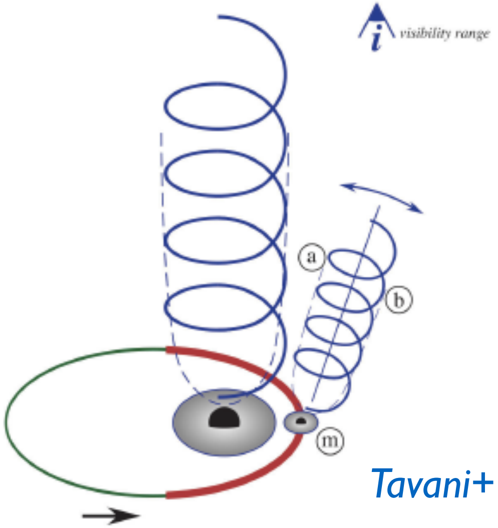

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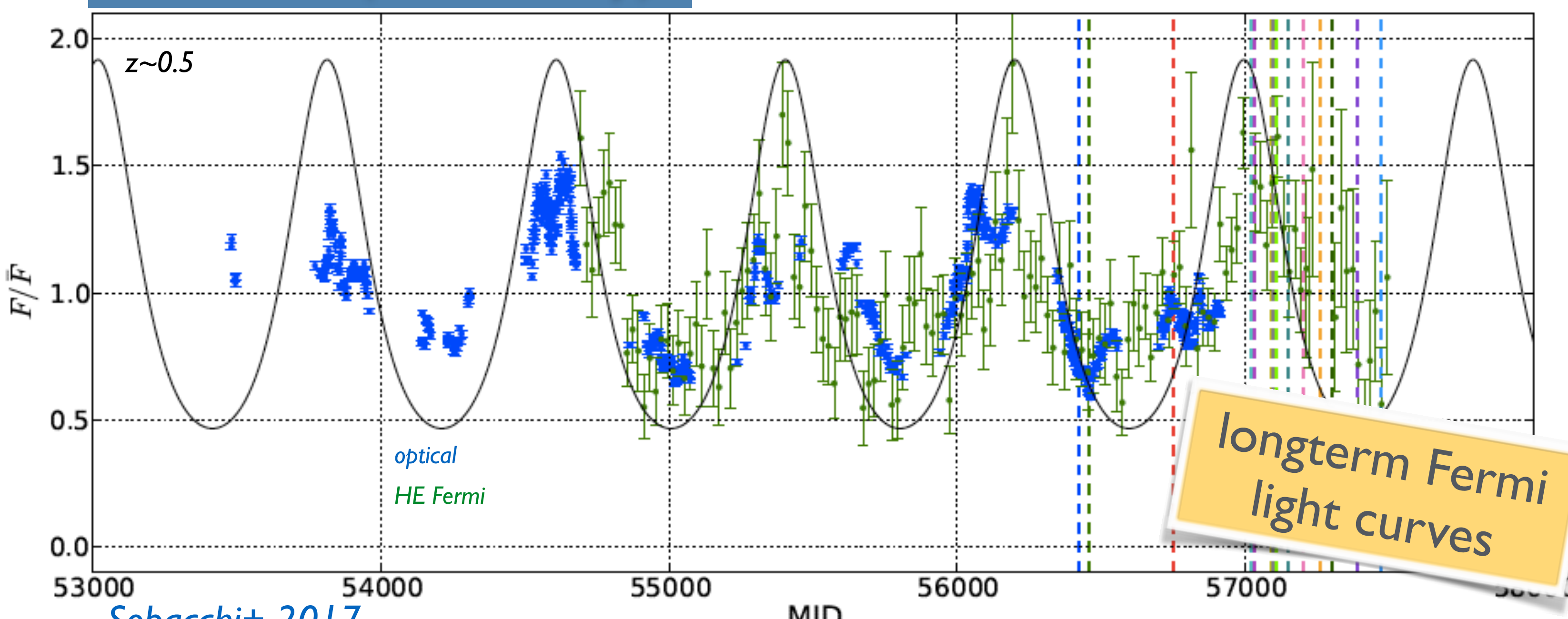

Sobacchi+ 2017…

year-type HE QPOs:

PKS 2155-304
Mkn 501
BL Lac
PKS 0426-380
PKS 0537-441
PKS 0310-243…

Ackermann+ 2015
Sandrinelli+ 2014,2016
Zhang+ 2017
Prokorov & Moragham 2017
Bhatta 2018…

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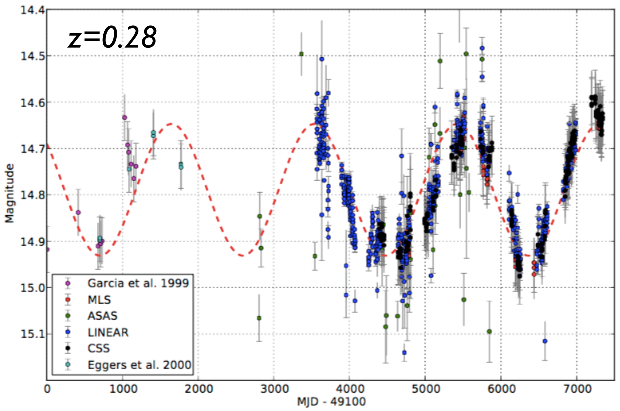

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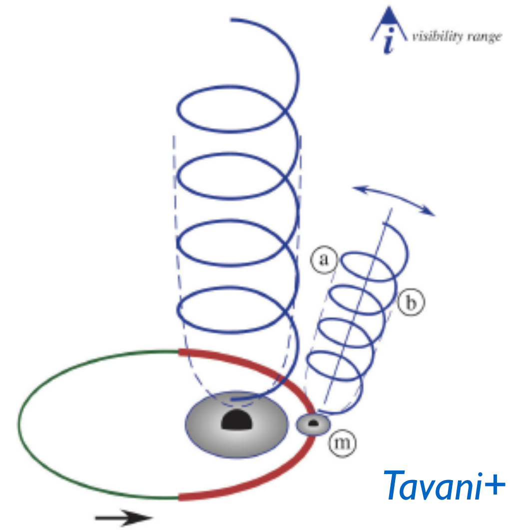

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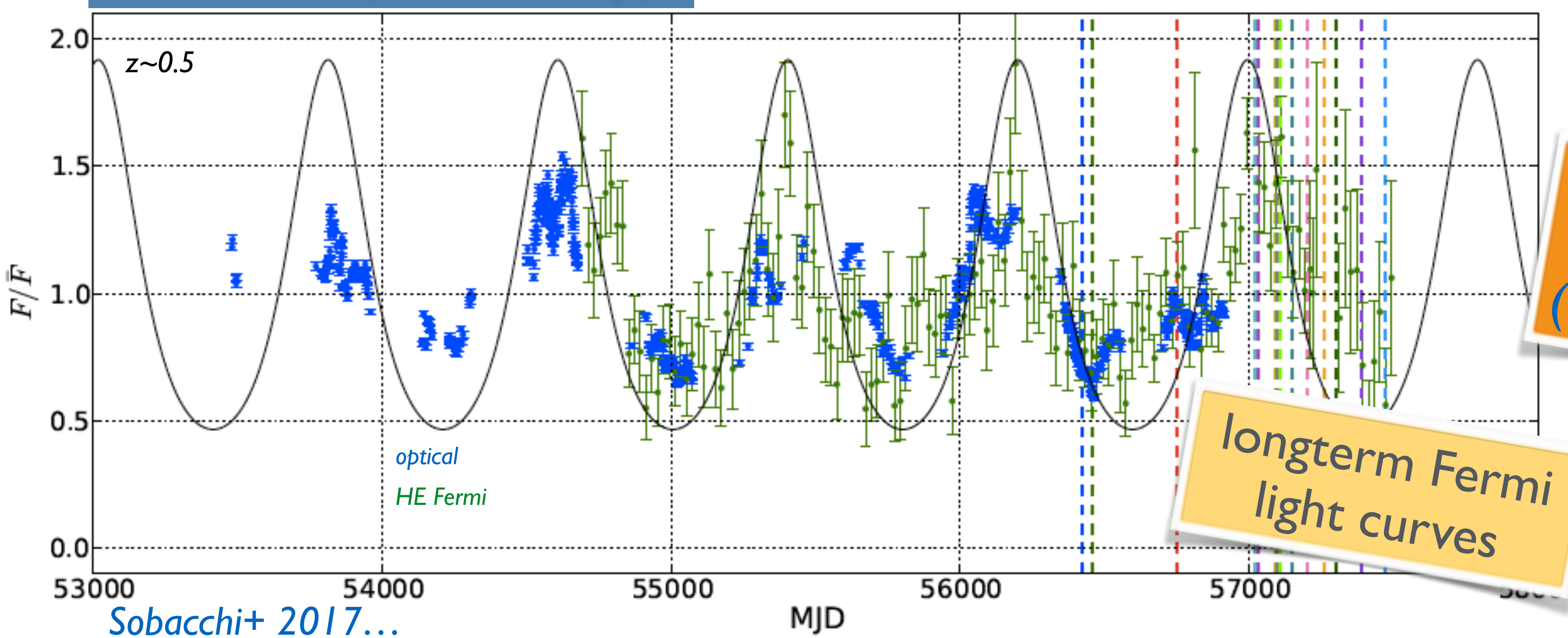

Sobacchi+ 2017…

longterm Fermi light curves

year-type HE QPOs:

PKS 2155-304

PKS 0310-243…

improve QPO analysis (Vaughan+ 2016)

Ackermann+ 2015
Sandrinelli+ 2014,2016
Zhang+ 2017
Prokorov & Moragham 2017
Bhatta 2018…

The (new) emergence of supermassive binary models

Hierarchical Galaxy Formation:

- *Radio-loud AGN hosted by elliptical formed by merging events*

Interacting Galaxies NGC 2207 and IC 2163
credit: NASA (Hubble, 2007)

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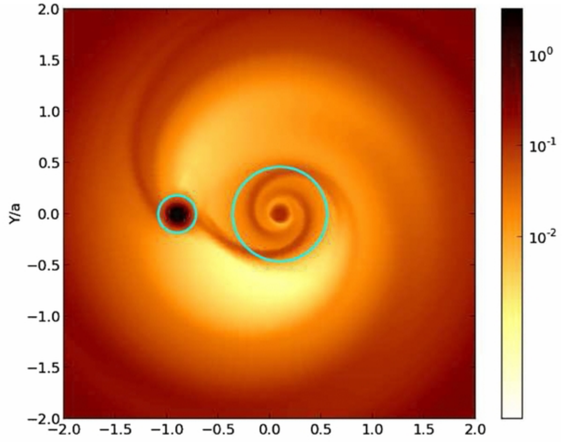
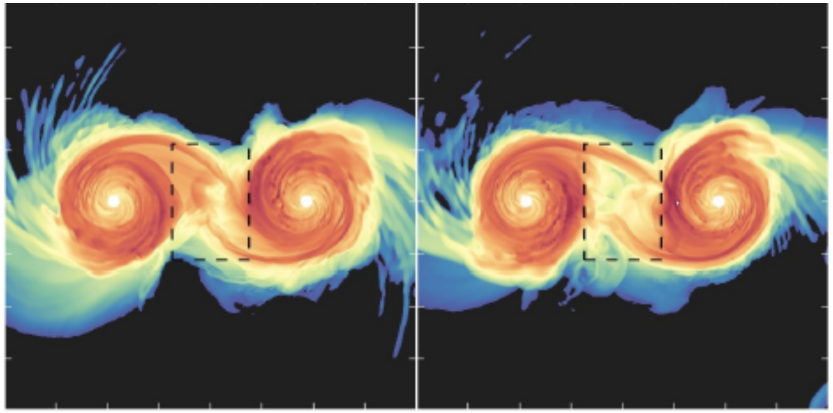
Evolutionary track of SBBHs:

- *circum-binary disk and BH mini-disks simulations*



Farris+ 2014



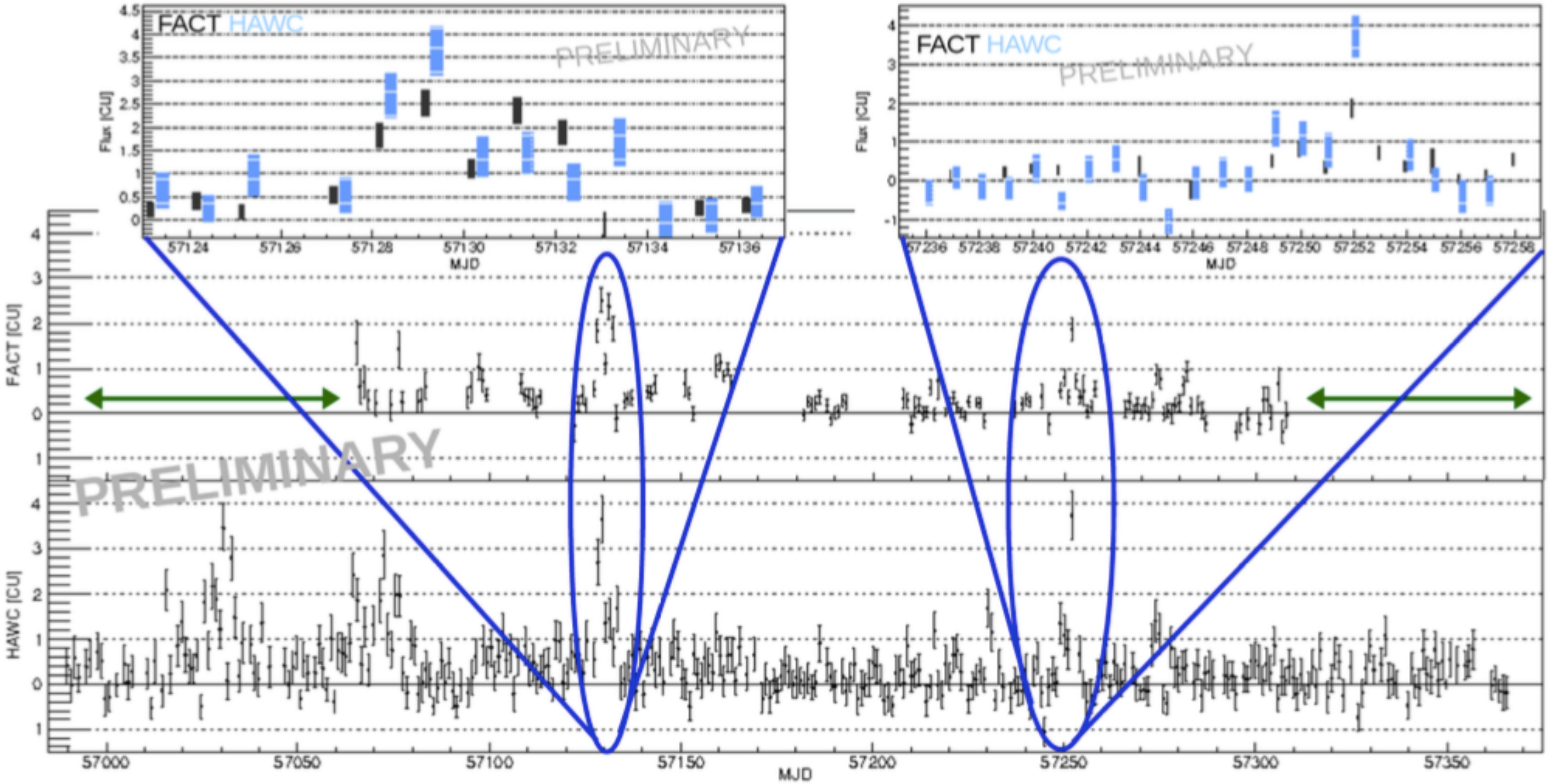
Bowen+ 2017

Longterm monitoring of bright blazars

biased (IACT) and unbiased light curves

characterizing longterm VHE variability

Mkn 501: Daily light curve by FACT (top) and HAWC (bottom) from Nov. 2014- Dec. 2015

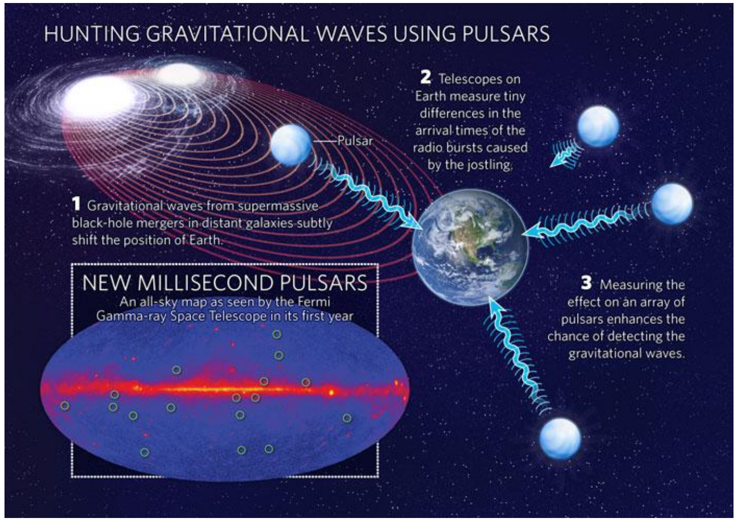


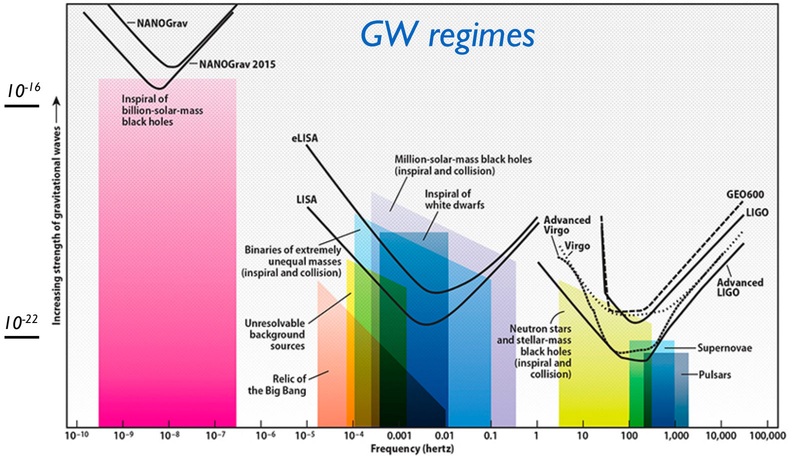
Dorner+ 2017 (Gamma2016)

- ***P ~ O(1 yr) implies very close binary & significant gravitational emission***
  - short gravitational lifetime T ~ (10^3-10^4) yr

    ⇒ *low probability*
  - PTA upper limit on gravitational background

    ⇒ *only 0.01 - 0.1% (BL Lacs & FSRQs)* *(Holgado+2018)*
  - should expect rather P ~ O(10 yr) *(Rieger+ 2007)*





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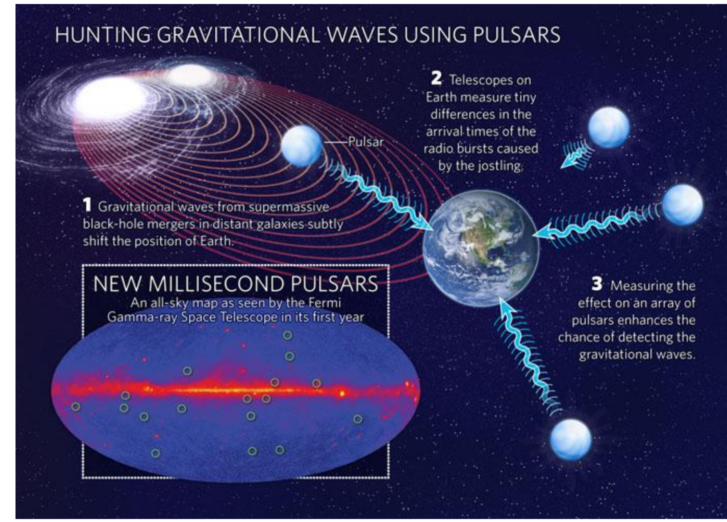
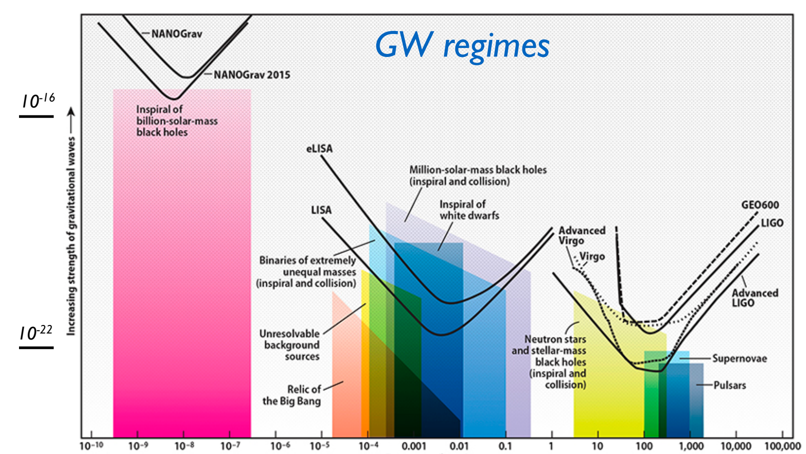


- ***Alternative scenarios:***
  - lighthouse model *(e.g., Camenzing & Krockenberger 1992)*

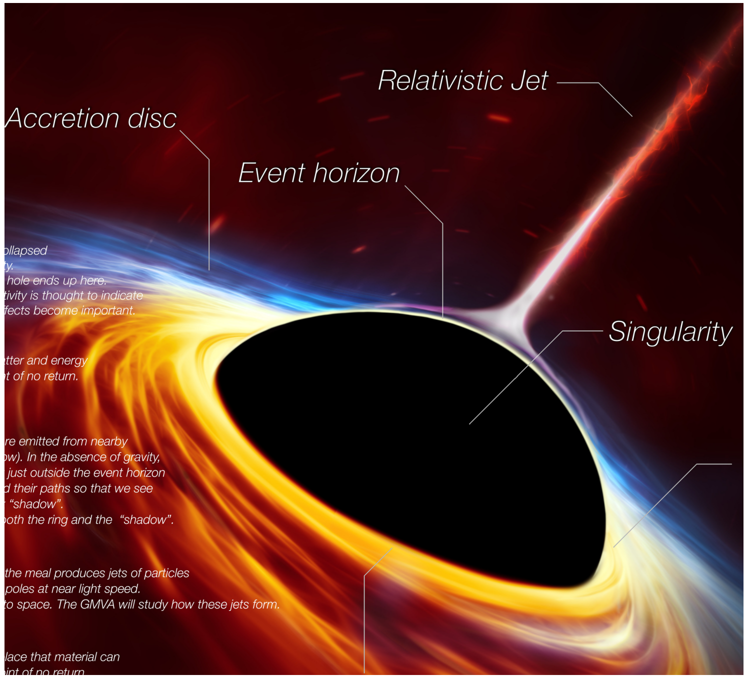
    ⇒ *outer jet-radius-constraints imply P < 2 yr* *(Rieger 2004)*
  - changes in accretion flow *(ADAF to SS)* *(Gracia+ 2003)*

    ⇒ *transition radius r_{tr} ~ 100 r_g*



Potential & Perspectives

- *characterising gamma-ray variability beyond minimum timescales is gaining momentum*
  - *log-normality, PSD, QPOs…*
- *making (obvious) use of current & upcoming experimental capabilities*
  - *photon statistics (CTA), longterm monitoring.…*
- *conceptual understanding needs "investment"*
  - *physical origin of variability & emission processes*
  - *BH - accretion - jet - link*



Thank you!